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memorandum

date July 10, 2020

to Preston Brown

from Michael Strom, Jason White

subject Lagunitas Creek – Floodplain Activation Flow Hydraulic Modeling Analysis

Introduction

This memorandum presents the methods, results, discussion, and conclusion of a hydraulic modeling study to better understand floodplain activation of winter habitat conditions for Central California Coast Coho Salmon in Lagunitas Creek. The Lagunitas Creek Watershed supports the southernmost stable population of Central California Coast Coho Salmon, and it is believed that Coho rearing in Lagunitas Creek is constrained by the availability of winter habitat (Stillwater, 2008). However, the flows of Lagunitas Creek are regulated by Peters Dam, which adheres to water board order WR 95-17. Dam operations currently modify downstream hydrology, which in turn affects instream flow conditions, connectivity to floodplain habitats, and geomorphic processes. The 2013 *Winter Habitat Enhancement Assessment* (KHE, 2013) determined that due to the regulated hydrograph Lagunitas Creek experiences reduced frequency, duration and magnitude of regular winter high flows, which has reduced the amount of inundated floodplain and side channel areas available for high flow refugia. The resulting distribution of floodplain habitat throughout the watershed across a range of winter flows, and the factors responsible for this habitat distribution are not well understood.

Environmental Science Associates (ESA, 2019) reviewed existing geographic, geologic, hydrologic, geomorphic, and vegetation conditions in the regulated portion of the watershed to develop a conceptual model of winter habitat. This review resulted in the delineation of three dominant reaches assumed to have similar winter habitat conditions across each reach. ESA then performed two-dimensional hydraulic modeling of the three reaches, covering 11 miles of Lagunitas Creek from the San Geronimo Creek confluence to the Highway 1 bridge, to elucidate the habitat distribution and governing factors over a range of winter flows. This approach has some limitations due to the availability of input data for such a large model domain. However, it provides a comprehensive, watershed-scale perspective on the hydraulics and floodplain activation across multiple winter flows. The next step in this study will be to collect strategically located field measurements over a winter for a more detailed assessment of habitat conditions at the habitat unit scale. The study will ultimately combine the field measurements and hydraulic modeling with the winter habitat conceptual model to better understand patterns of floodplain activation and winter habitat conditions for Coho in Lagunitas Creek.

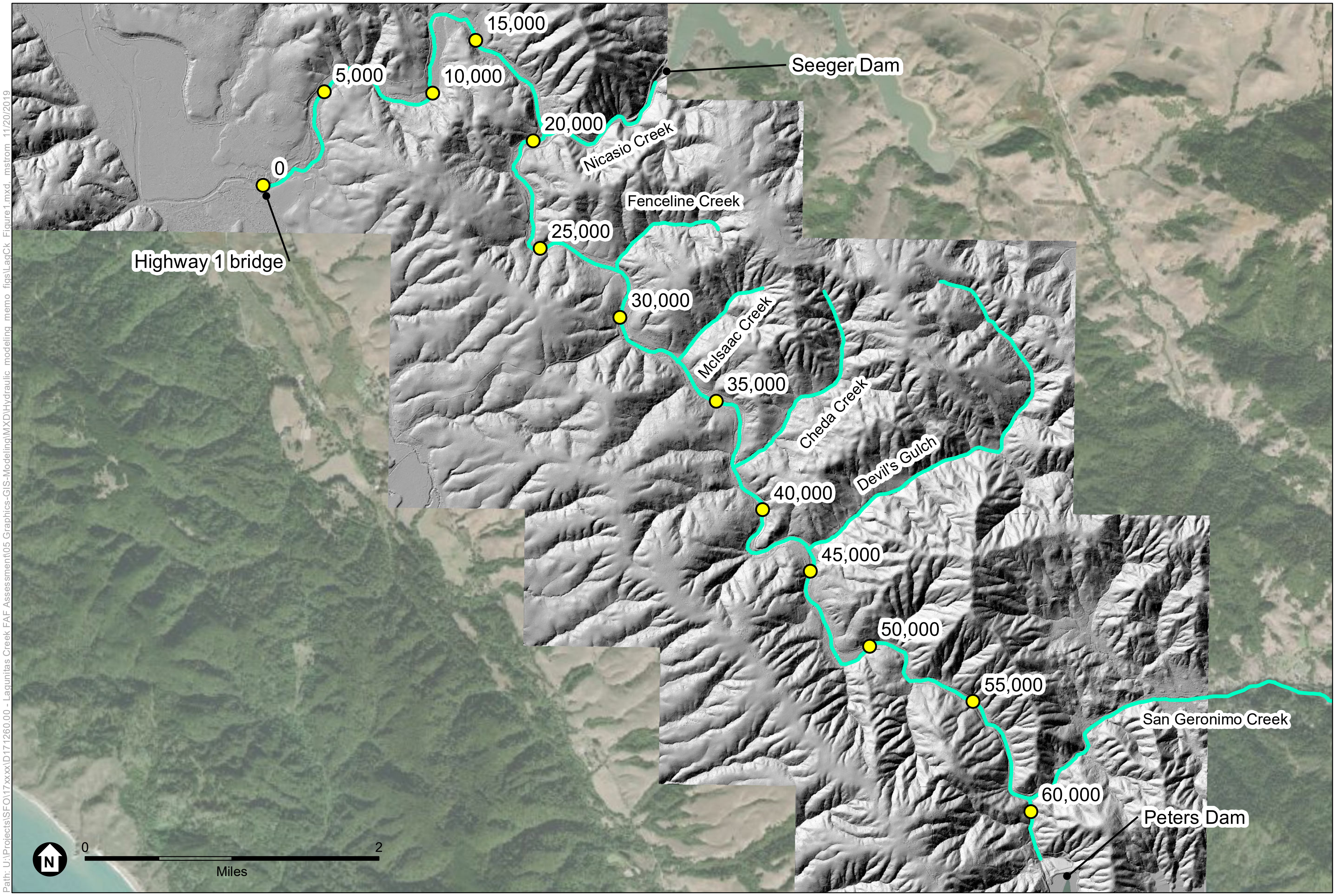
Methods

Two-dimensional (2D) hydraulic modeling provides an efficient tool for simulating the spatial distributions of flow depth and velocity that are relevant for predicting the habitat occurrence and suitability for salmonid rearing. A 2D model predicts the depth-averaged velocity distribution across the full planform spatial extent of the flow as well as more accurately predicts the inundation of complex off-channel features, which is critical for evaluating whether the channel fringe, side channels, alcoves, and other potential habitat features exhibit suitable depth and velocity for rearing. Given modern computing capabilities, 2D models are relatively efficient to run across large spatial domains. The model used for this study was developed in HEC-RAS version 5.0.7 with a domain extending 11 miles from the confluence of San Geronimo Creek to the Highway 1 bridge. A LiDAR dataset was used as the basis for the topography in the model, and five winter flows were modeled including three base flows and two minor flood flows. The following sections describe the steps for creating the hydraulic model and processing the results.

Topography

The primary input for a 2D hydraulic model is the topographic surface across which flow is simulated. Compared with ground-based survey methods such as use of a theodolite, LiDAR datasets typically have the advantage of providing a higher density of data points, reducing the need to interpolate between more widely spaced cross sections or points when constructing a topographic surface suitable for 2D modeling. The main challenges with using LiDAR are the presence of dense vegetation that obscures the bare-earth ground surface and water in the channel that obscures the true channel bathymetry, as these datasets are most often collected using LiDAR that cannot penetrate water. There is therefore a tradeoff in which each individual data point in a LiDAR survey is potentially less accurate than a point taken with a theodolite, but many more points can be collected.

ESA built a bare-earth topographic surface for the project area (Figure 1) using data from the Golden Gate LiDAR Project (SFSU, 2010), which was collected in 2010 at an approximate resolution of 2 meters. The ground return data points were segregated from the non-ground return data such as vegetation points, and then converted to a surface using TIN interpolation. Due to reduced ground point density along the channel in areas with a dense riparian canopy, artifacts in the surface had to be manually corrected to avoid significantly influencing the hydraulic results. Specifically, spikes in the surface due to poor interpolation of sparse ground points created artificial backwaters in the channel that complicated the interpretation of velocity, depth, and wetted area trends, especially at lower discharges. Figure 2 shows an example of this. Surface spikes along the channel that were responsible for abrupt downstream drops in water surface elevation of about 2 ft and greater were targeted for manual correction as these had associated backwaters that were particularly extensive.



SOURCE: ESA 2019

Lagunitas Creek - Floodplain Activation Flow Hydraulic Modeling Analysis

Figure 1
Lagunitas Creek Watershed Overview

ESA

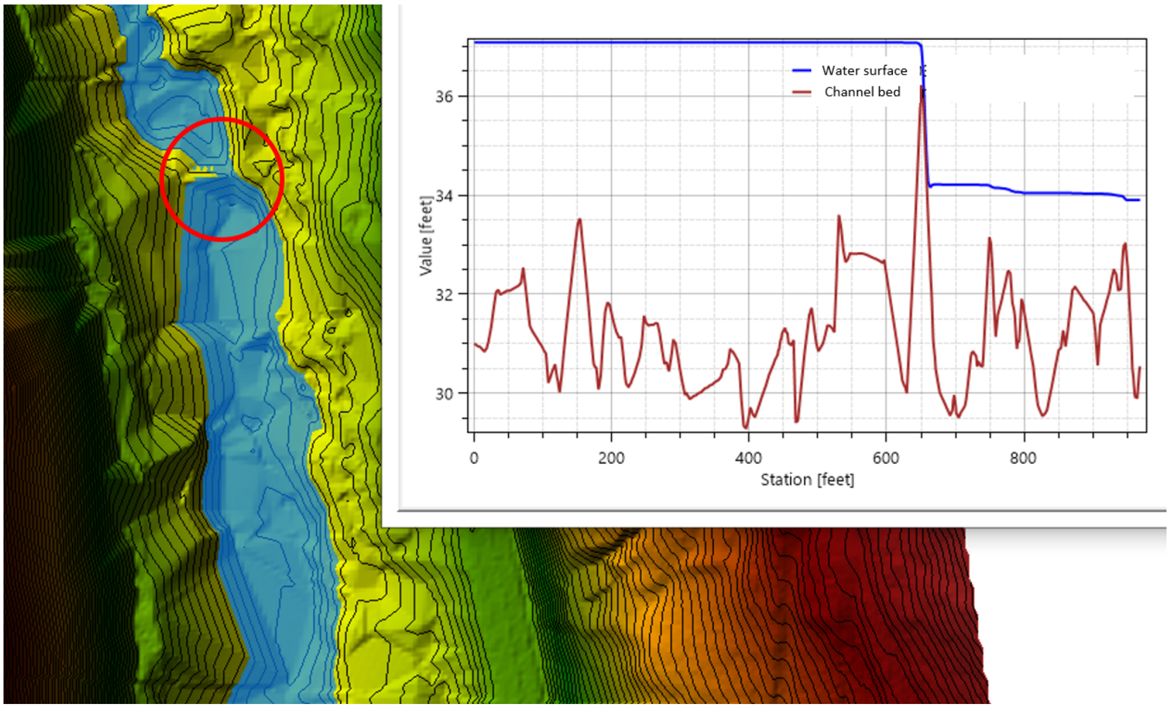


Figure 2. Plan and profile views of a surface interpolation artifact ("spike" circled in red) and associated artificial backwater at 65 cfs. Surface contours are 2 ft.

Roughness

With a topographic surface free of major artifacts, the next step was to delineate hydraulic roughness regions that the model uses in computations to determine resistance to flow. Channel and overbank roughness regions were approximately delineated using the ground surface and aerial imagery as a reference. The channel and overbank were assigned Manning's n roughness values of 0.075 and 0.1, respectively, based on a calibration performed by ESA (2018) for a one-dimensional model in the vicinity of the SPAWN offices. While the channel and overbank roughness likely deviate from these values along the full model domain of the current study, these values were applied throughout the model given the lack of additional calibration data and the objective of the current study to more coarsely model the hydraulics across a very large domain.

Computational mesh

The computational mesh was created extending from the confluence with San Geronimo Creek downstream to the Highway 1 crossing. A mesh cell size of 5 ft by 5 ft was used given the software limitations on the number of cells allowed, which prevented the use of a smaller cell size. Additionally, given the channel width and resolution of the LiDAR ground points, particularly in areas with dense canopy, 5 ft by 5 ft was considered an appropriate minimum cell size to use for this analysis.

Boundary conditions

The model was run for the five flows listed below (ESA, 2018) with 65-200 cfs intended to represent mid to high winter base flows. The two lowest flows, 65 cfs and 155 cfs, were determined through an ecohydrology analysis of the flow data at the Samuel P. Taylor USGS gage. These flows are predicted to support the development of plankton-based food webs on the floodplain that generate a large amount of food for juvenile salmonids (ESA, 2018). Research varies on the true time it takes, but biologists tend to agree upon a duration of 2 weeks as supporting primary productivity. Although corresponding research has not been published for smaller coastal watersheds, ESA adopted this metric as a way of evaluating inundation patterns in Lagunitas Creek. The middle flow, 200 cfs, appears to be in the high range of winter base flows between winter storms (ESA, 2018). The two highest flows, 346 cfs and 1570 cfs, are peaks flows associated with winter storm events of relatively high probability of occurrence that are close to bankfull discharge and provide a benchmark of channel-floodplain connectivity. Each flow was held constant along the full creek model domain instead of introducing flow inputs at each tributary as a more detailed hydrologic characterization of the watershed was not part of this higher level modeling exercise.

- **65 cfs:** Avg. 2- and 4-week flow duration for Feb-Mar; mid-range winter flow
- **155 cfs:** Max. 2-week flow duration; high-range winter flow
- **200 cfs:** high-range winter flow
- **346 cfs:** 1.0-year event
- **1570 cfs:** 1.5-year event

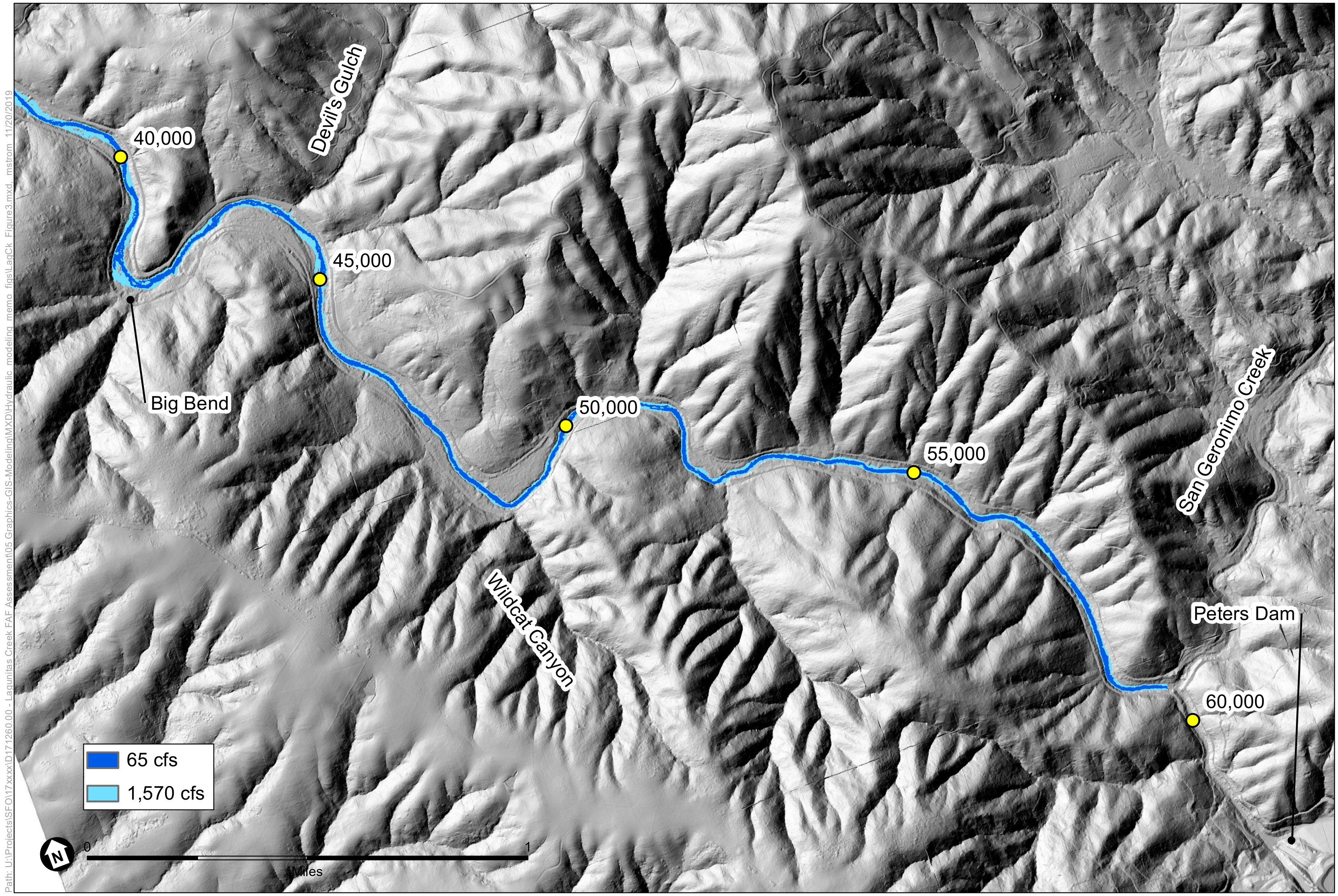
The model was run until steady state conditions were reached, i.e., hydraulic variables were no longer changing for a given flow. Based on the timing of the LiDAR flight, there was approximately 20 cfs in the channel while the LiDAR was being collected. Since the LiDAR did not capture the true bathymetry, 20 cfs was subtracted from each of the five flows to roughly avoid double-counting the presence of this flow. A 0.02% normal depth slope was applied as the downstream boundary condition.

Converting hydraulic model output into Coho rearing habitat suitability metrics

Depth and velocity results for each flow were exported from HEC-RAS to ArcGIS as rasters, and average depth, average velocity, wetted area, and area of suitable juvenile Coho habitat were computed within polygons spaced every 100 ft along the channel. These series were then converted to 1000 ft moving averages to reveal broader scale patterns. Suitable rearing habitat was assumed to exhibit a depth of less than 3.3 ft and a velocity of less than 1.3 ft/s per the literature review by SPAWN (2019), but note that the regions in the model results mapped out as meeting these criteria should be interpreted as potentially suitable habitat given the lack of model calibration and the limitations in the model input data. For example, the modeled depths are likely to be underestimated due to the lack of bathymetric data, which is especially true for the deeper sub-reaches downstream of the Nicasio Creek confluence. Lastly, the difference in suitable habitat area between flows was computed to more clearly reveal how habitat changes as a function of flow.

Results and Discussion

Figures 3 through 5 show maps of the 65 and 1570 cfs wetted areas across the full model domain. Figures 6 through 10 show the longitudinal series of average depth, average velocity, wetted area, suitable habitat area, and the difference in suitable habitat area between flows. The locations of major tributary confluences and maximum suitable depth and velocity are included for reference, and the channel bed profile is included to show general changes in slope. Note that the channel centerline used to extract surface elevations doesn't exactly follow the tortuous path of lowest elevation, and hence the many local spikes in the profile.

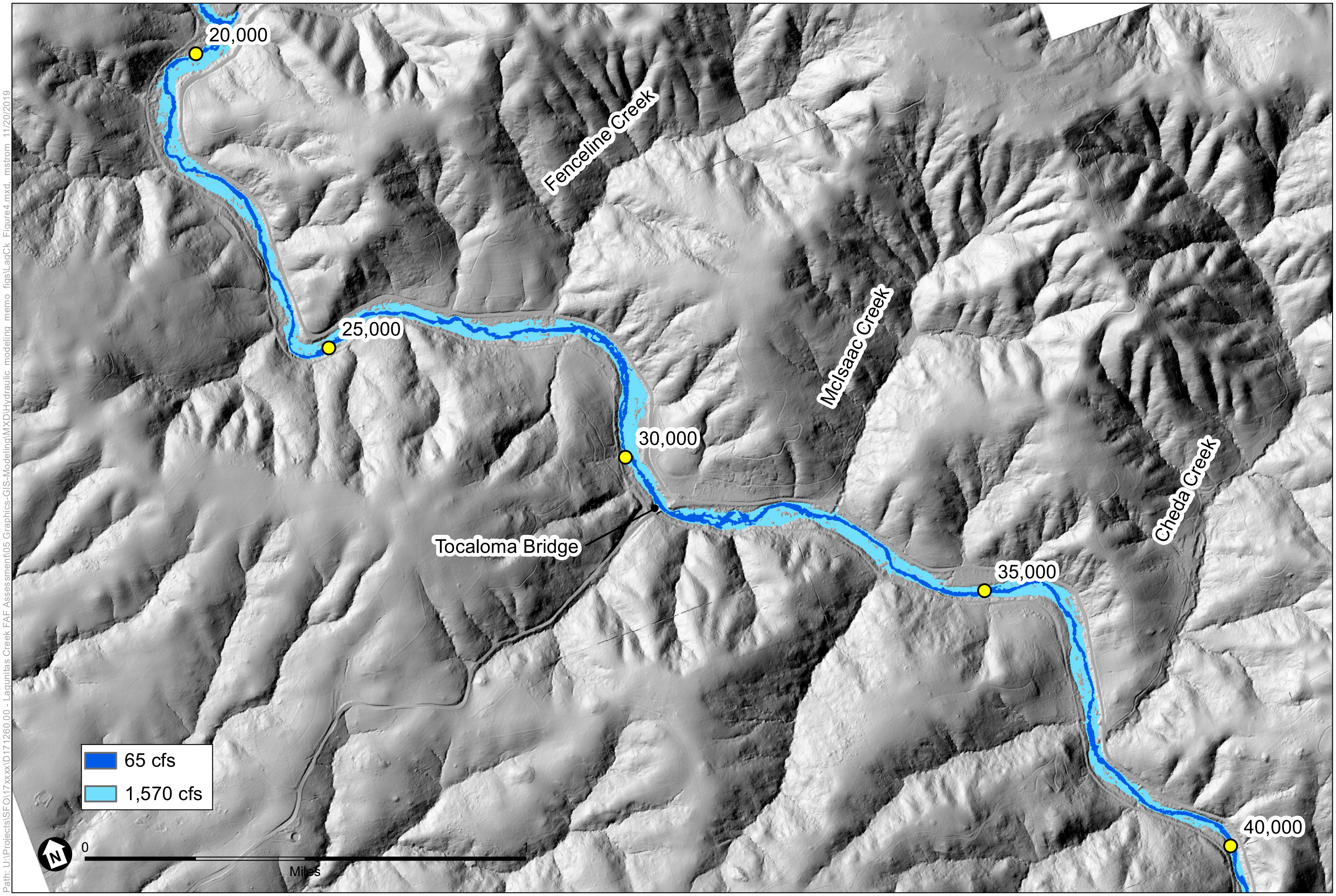


SOURCE: ESA 2019

Lagunitas Creek - Floodplain Activation Flow Hydraulic Modeling Analysis

Figure 3
Lagunitas Creek Modeled Wetted Area at 65 and 1,570 cfs (Upstream of Station 40,000)

ESA

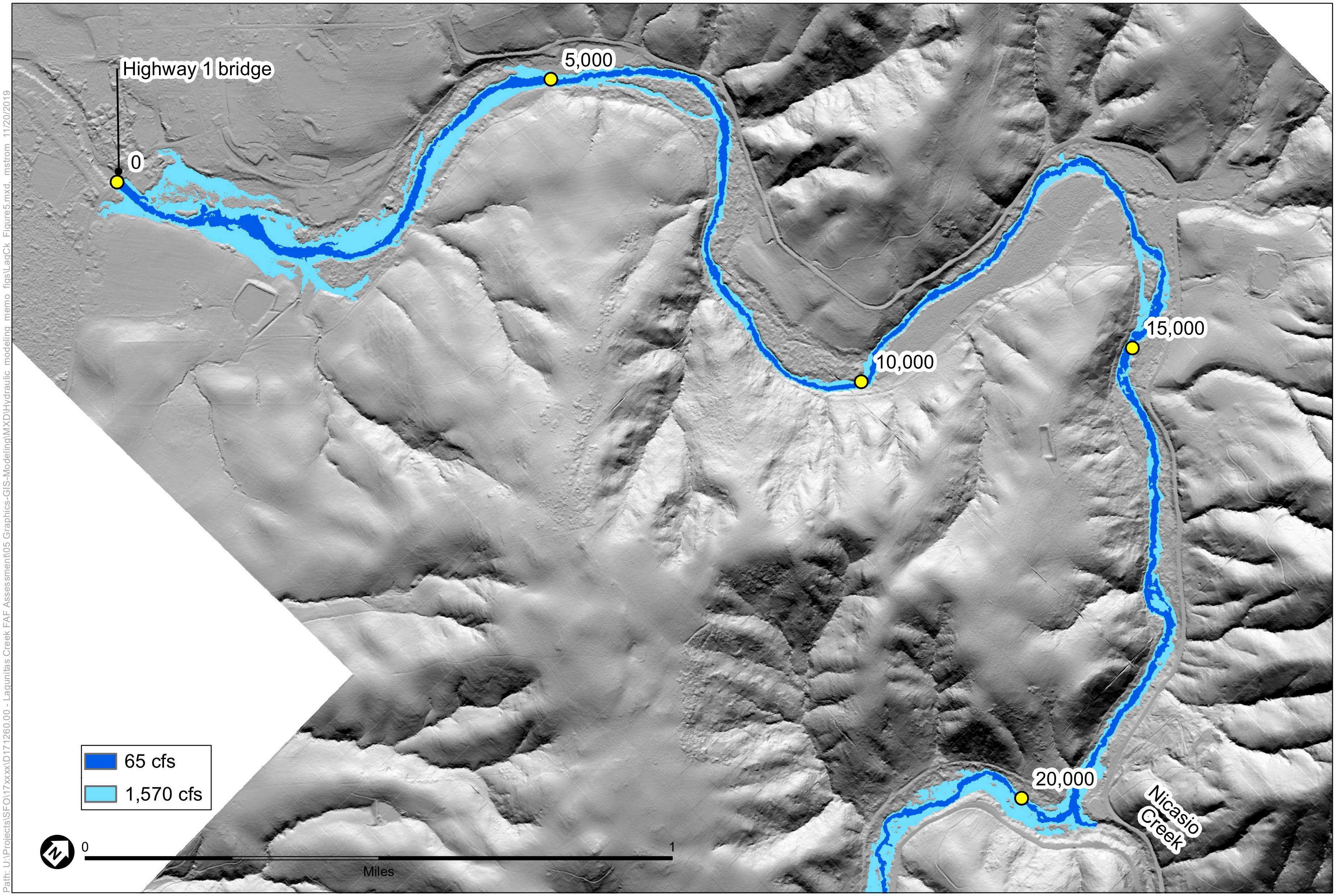


SOURCE: ESA 2019

Lagunitas Creek - Floodplain Activation Flow Hydraulic Modeling Analysis

Figure 4
Lagunitas Creek Modeled Wetted Area at 65 and 1,570 cfs (Station 40,000 to 20,000)

ESA



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SOURCE: ESA 2019

Lagunitas Creek - Floodplain Activation Flow Hydraulic Modeling Analysis

Figure 5
Lagunitas Creek Modeled Wetted Area at 65 and 1,570 cfs (Downstream of Station 20,000)

ESA

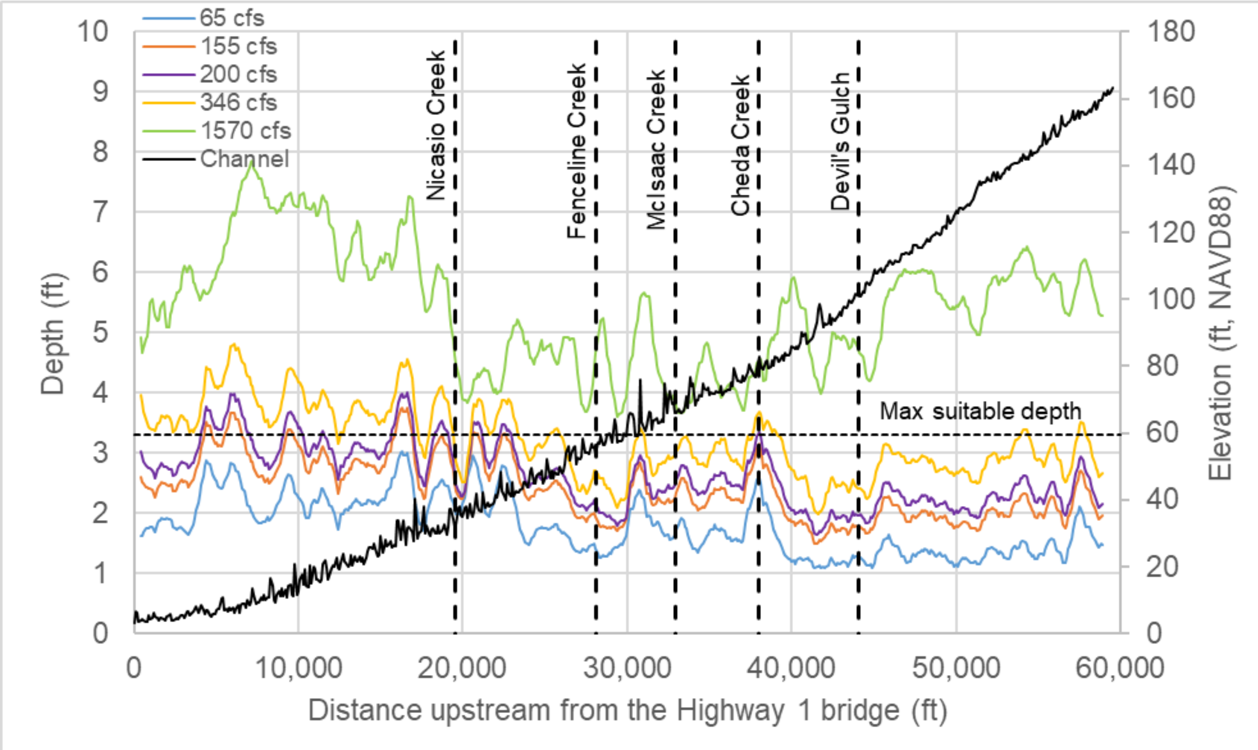

Figure 6. Longitudinal profiles of average depth for the five flows.

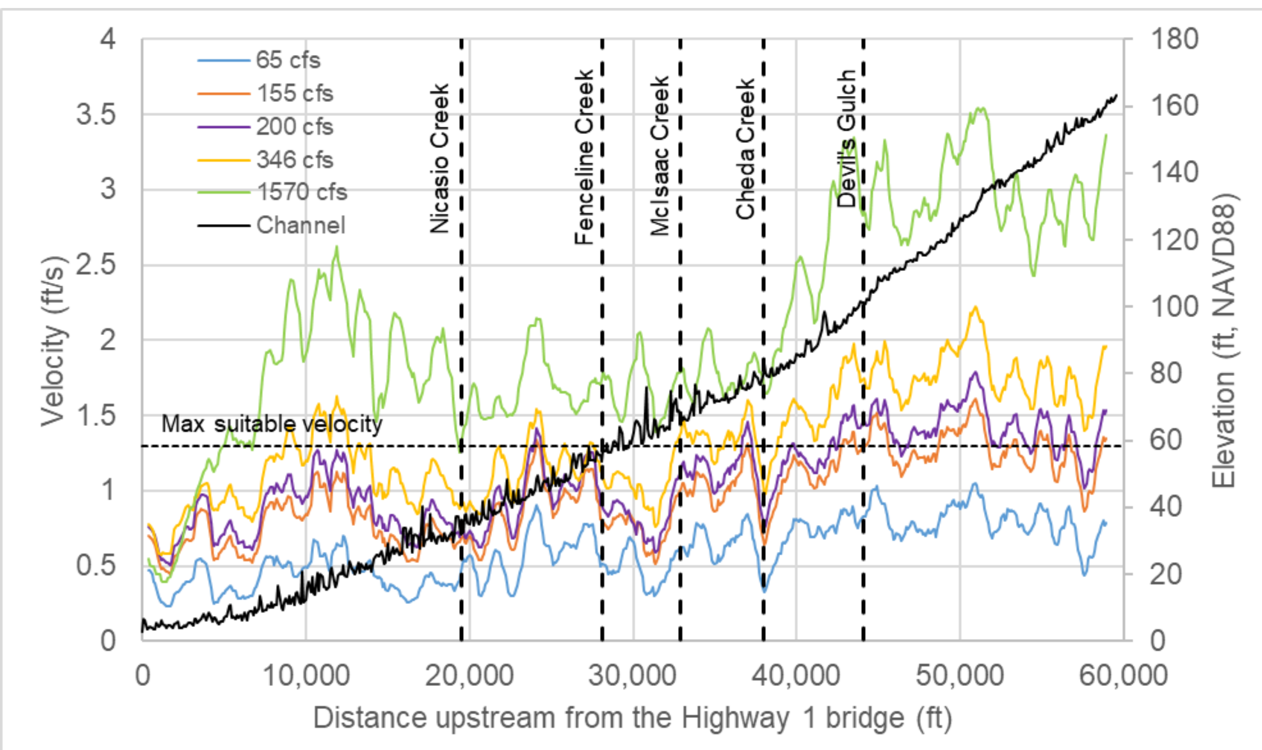

Figure 7. Longitudinal profiles of average velocity for the five flows.

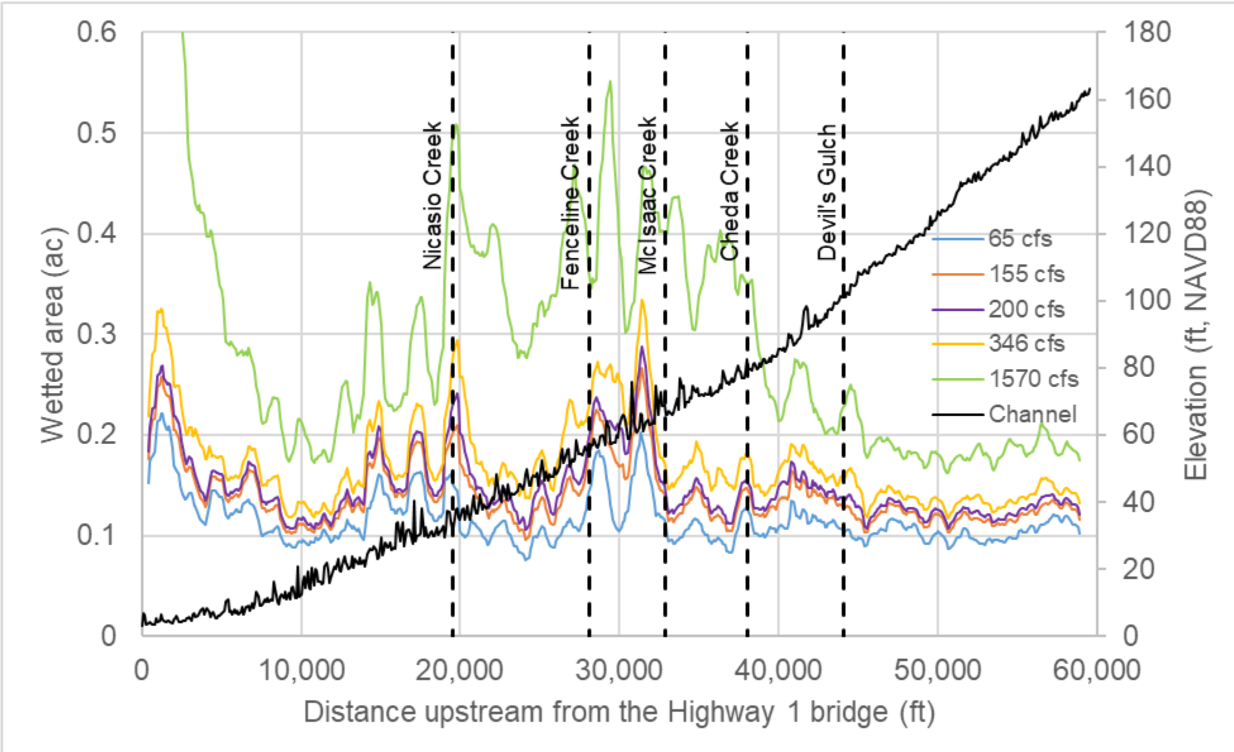

Figure 8. Longitudinal profiles of wetted area for the five flows. The 1570 cfs profile reaches a max of 0.96 ac in the downstream reach and was cut off for legibility of the other profiles.

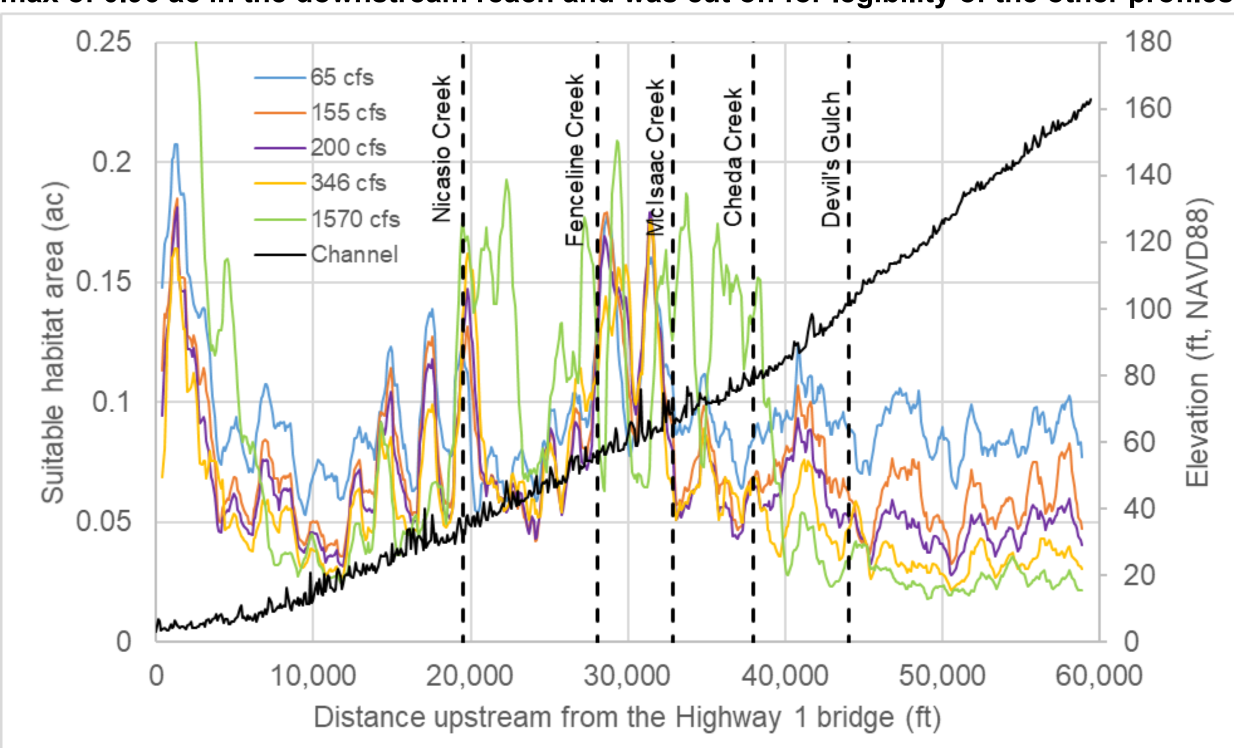

Figure 9. Longitudinal profiles of suitable habitat area for the five flows. The 1570 cfs profile reaches a max of 0.45 ac in the downstream reach and was cut off for legibility of the other profiles.

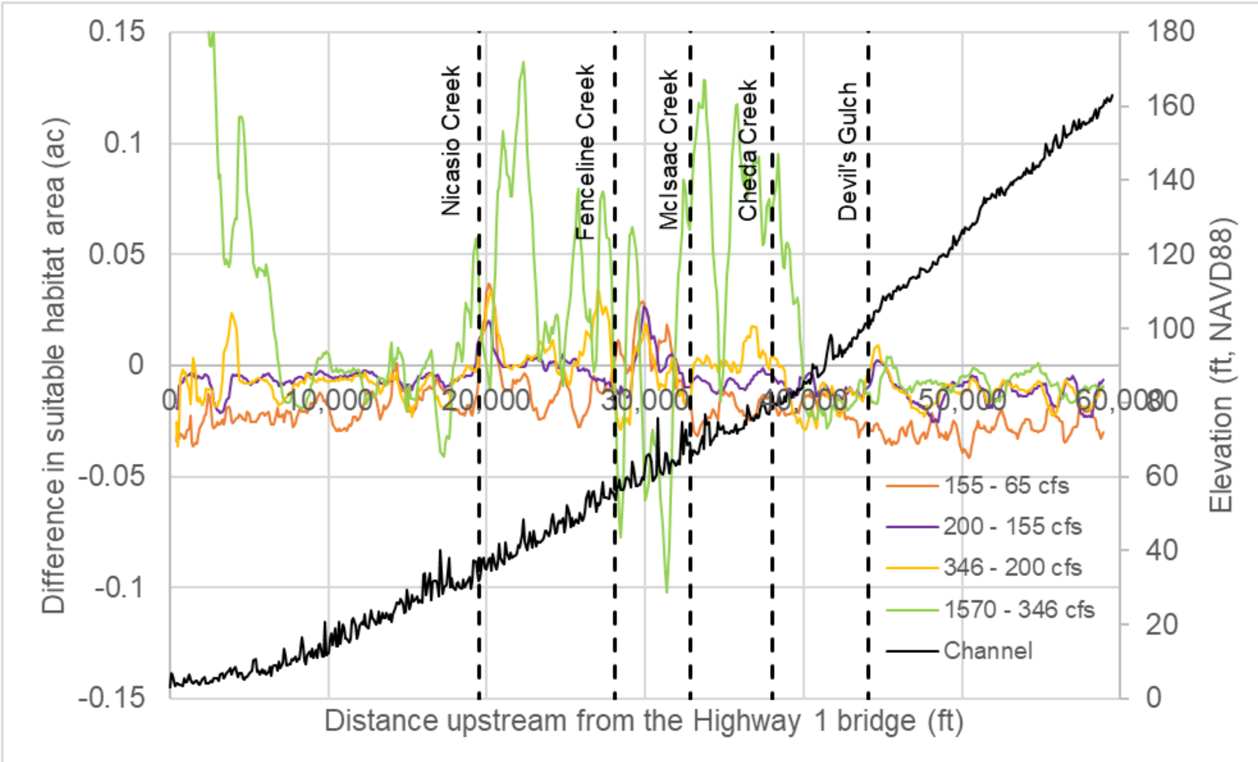

Figure 10. Longitudinal profiles of suitable habitat area differences between the five flows. The 1570 – 346 cfs profile reaches a max of 0.36 ac in the downstream reach and was cut off for legibility of the other profiles.

Upper Reach: Upstream of station 40,000

The Upper Reach, being the steepest, tends to be shallower and faster than the other reaches (Figures 6 and 7). There is a clear inverse relationship between the flow magnitude and the area of suitable winter rearing habitat (Figure 9). Velocity is the most limiting factor for habitat suitability, with unsuitable velocities emerging at 155 cfs and becoming more extensive at higher flows. Depth is less variable than velocity along the reach for a given flow and less limiting for habitat suitability as suitable depths occur through the 1-year flow. With increasing flow, the habitat suitability both decreases (Figure 10) and becomes less variable (Figure 9). This suggests that the limited backwater and channel fringe habitat locations that do exist in the Upper Reach during mid-range winter flows get drowned out by more uniformly unsuitable conditions during high-range winter and minor flood flows. A possible implication of this sensitivity is that relatively small reductions in velocity, such as large woody debris structures, could increase the area of suitable habitat during high-range winter flows. However, the wetted area results in Figure 8 indicate a relatively uniformly confined valley bottom and incised channel with minimal floodplain such that the wetted area doesn't vary significantly along the channel for both a given flow as well as across the flows. This suggests that the potential for creating suitable winter habitat is ultimately constrained by the confined valley setting as the adjacent hillslopes greatly limit the historic floodplain area that could be reconnected. Suitable rearing habitat could potentially be made more available in this reach for the low-range storms and winter baseflow with the addition of significant roughness features that would reduce in-channel velocities on a micro scale. The addition of more large woody debris jams in this reach could reduce velocities somewhat for low to mid-range base flows below 155 cfs to promote more suitable rearing habitat. However, as discharge increases above mid-range base flows, large habitat structures would likely experience more turbulent conditions or would be drowned out by larger storms and would not provide suitable rearing habitat.

Middle Reach: Station 40,000 to 20,000

The Middle Reach is slightly deeper and markedly slower than the Upper Reach such that neither depth nor velocity is a dominant limiting factor for habitat suitability through the 1-year flow. There is overall more suitable habitat in the Middle Reach than upstream due to the lower gradient and velocity, and flow magnitude and suitable habitat area are also less inversely related (Figure 10). While suitable habitat area decreases slightly or stays the same across the winter base flows, the suitable habitat area actually shows a significant increase through the 1.5-year flow. Figure 4 shows the presence of more active floodplain that becomes inundated during the 1.5-year flow and provides shallow, low velocity habitat. These model trends reflect the lower channel slope and less confined valley setting in the Middle Reach that enable more extensive backwaters and the activation of side channels and floodplain features across a range of flows. This enhanced lateral connectivity is also evident in the wetted area profiles that show a larger rate of change in wetted area across the five flows compared to the Upper Reach, which is accompanied by a smaller rate of change in velocity given the lateral space for flow to spread out.

More specifically, the wetted area and suitable habitat area profiles suggest at least two different sets of conditions within the Middle Reach. Between approximately the Cheda and McIsaac Creek confluences and between the Fenceline and Nicasio Creek confluences, the wetted area exhibits a similar distribution along the channel for a given flow. There's a moderately large increase in wetted area here across the four lower flows, certainly larger than that in the Upper Reach, but the suitable habitat area only drops slightly with increasing flows and notably much less so than upstream. This appears to be due to the activation of more channel fringe and off-channel habitat with increasing flow that counters the loss of habitat in the main channel as faster, deeper conditions emerge. In these two sub-reaches between the tributary confluences, 1570 cfs shows a significant increase in both wetted area and suitable habitat area as most of the floodplain becomes inundated with slow, shallow flow. These sub-reaches contrast with the sub-reach between the McIsaac and Fenceline Creek confluences. With the exception of the Tocaloma Bridge at station 31,000 that abruptly narrows the wetted area, this sub-reach exhibits extensive wetted area and suitable habitat area across all flows as a sizeable portion of the valley bottom is already activated under winter base flows via side channel and alcove features. While the two aforementioned sub-reaches don't significantly lose habitat area with increasing flow as is the case for the Upper Reach, the 1570 cfs model results for the McIsaac to Fenceline Creek sub-reach suggest that there is room in the valley bottom to greatly increase the available habitat in these two sub-reaches during mid to high winter base flows.

For reference, the 1570 cfs water surface elevation through the Middle Reach is on average about 4 ft higher than at 346 cfs, so substantial increases in habitat could be achieved if the bed aggraded by approximately this depth via restoration actions that induce deposition, such as channel width expansions. Alternatively, or in conjunction, portions of the floodplain could be lowered to promote inundation at lower flow. Conversely, maintaining flow rates in the channel at the 1.5-yr storm event to activate floodplain areas in this reach would result in extended duration of floodplain inundation at the point when suitable habitat rapidly becomes more available. However, releasing flows to meet this rate is likely not feasible except for very brief occurrences because the flow from Peter's Dam can only be released with a maximum discharge of 50 cfs, whereas the 1.5-yr event is 1570 cfs. Likewise, increasing flow rates from the dam to increase the duration and frequency of flows around 1570 cfs would simultaneously reduce the amount of suitable habitat in the Upper Reach and Lower Reach where the channel is confined. Given the constraints and drawbacks of maintaining flows at this rate, channel width expansions that induce bed aggradation could be a better alternative for connecting the channel to the floodplain and activating floodplain habitat features.

Lower Reach: Downstream of station 20,000

In the Lower Reach, downstream of the Nicasio Creek confluence, the depth for the four lower flows is moderately higher than in the Middle Reach, although the true depth is likely considerably greater, especially closer to the Highway 1 bridge, due to the discrepancy between the LiDAR-based surface and the true channel bathymetry. From station 20,000 to around 6,000 the depth and wetted area at 1570 cfs are significantly higher and lower, respectively, than in the Middle Reach. Wetted area and average velocity even attain minimum and maximum values, respectively, around station 12,000 at 1570 cfs despite much lower valley confinement here compared to station 20,000 to 14,000 (Figure 5). This reflects the highly incised channel conditions that characterize much of the Lower Reach (Napolitano, 2014), which require much larger than a 1.5-year event to inundate the adjacent terraces.

The suitable habitat area profiles are difficult to assess in the Lower Reach due to large uncertainties with the actual bathymetry. This is particularly true downstream of station 6,000, which shows a very large increase in wetted area and habitat, but this may be mostly artificial as the full conveyance area of the channel is not being represented in the model. In areas where the model predicts suitable velocity, depth may in reality be greater than is suitable. However, there do appear to be local peaks in suitable habitat area around station 15,000 and 18,000 where off-channel features are located. Overall, based on the broad terraces that are present in the Lower Reach, particularly downstream of station 14,000, there appears to be enormous potential for increasing suitable habitat area at winter base flows if it were possible to reestablish and maintain floodplain connectivity. While incised channel conditions characterize both the Lower and Upper Reaches, the Lower Reach appears to have inherently greater habitat restoration potential due to the much lower valley confinement. Given that the Lower Reach is located in the most depositional position of the watershed where the channel slope flattens, width expansions of the incised channel into the adjacent terraces could work in tandem with the flattening bed slope to induce deposition, elevate water levels, and activate significant habitat area.

Modeling benefits and limitations

This hydraulic modeling analysis provided more detail regarding winter habitat conditions than possible with the watershed-scale field reconnaissance as part of the conceptual model by more explicitly linking specific winter flows to spatial distributions of depth and velocity. At a coarser scale, the model does currently provide a useful tool for analyzing the relative differences in winter flow hydraulics throughout the watershed and what these differences mean for winter habitat conditions and restoration potential. However, shallow and low velocity areas including smaller scale topographically subtle features such as channel fringe are likely not well represented in the topographic surface due to lower LiDAR ground point resolution under the riparian canopy, so the model likely underestimates the extent of suitable habitat. Given uncertainties with the model results due to data limitations across the large model domain, targeted field measurements in select reaches will provide more detail on habitat unit scale hydraulics.

Conclusion

Winter habitat conditions

The hydraulic modeling results for the regulated segment of Lagunitas Creek reveal both similarities and differences in habitat conditions across the three main reaches. In the Upper Reach, the channel is steep and confined by the adjacent valley hillslopes, which provides very little floodplain area beyond the channel as evidenced by limited wetted area extending laterally from 65 cfs to 1570 cfs. As a result of the steep channel slope and high hillslope confinement, velocities increase as flow increases, thereby decreasing winter habitat suitable for Coho rearing. Based on the model results, the Upper Reach of Lagunitas Creek does not appear to provide habitat conditions that are conducive to Coho winter rearing beyond mid-range winter base flows.

The Middle Reach has a lower channel slope with a broad floodplain and numerous off-channel features that are engaged by the various winter flows modeled. As these features become activated by increasing winter flows, the amount of habitat suitable for Coho rearing increases. There are isolated increases in habitat suitable for Coho rearing as flow increases from 65 cfs to 155 cfs, and from 155 cfs to 200 cfs. There is a more notable increase in suitable habitat from 200 cfs to 346 cfs followed by a significant increase from 346 cfs to 1570 cfs as flows spill out of the channel banks onto the broad floodplain.

In the Lower Reach, conditions become confined again as the channel is incised between terraces. Similar to the Upper Reach, much of the Lower Reach has minimal floodplain area beyond the channel as shown by limited wetted area extending laterally from 65 cfs to 1570 cfs for station 20,000 to 6.000. Consequently, the highly incised channel regions of the Lower Reach provide relatively modest area of habitat suitable for Coho rearing.

These model results are overall consistent with the observations presented in the watershed conceptual model, which found that the regulated segment of Lagunitas Creek can be broken into three main reaches that each exhibit certain winter habitat conditions.

Winter habitat improvement potential

These hydraulic modeling results provide some clarity in terms of the potential to improve winter habitat conditions through various restoration actions across the regulated segment of Lagunitas Creek.

First, the Middle Reach offers restoration potential in terms of floodplain habitat. The water surface elevation difference between 346 cfs and 1570 cfs is on average about four feet. Given the operating constraints of Peter's Dam and the negative effects on the Upper and Lower Reaches of maintaining flows greater than the 1.5-yr storm, the potential to increase floodplain activation in the Middle Reach lies in either raising the winter flow water surface elevation through bed aggradation or lowering the floodplain. Lowering the floodplain across all of the Middle Reach has feasibility limitations in terms of cost and impacts to the existing riparian corridor. Alternatively, there are numerous less costly and impactful restoration actions that have been found to promote raising the channel bed and/or water surface elevation, including adding large wood, beaver dam analogs, constructed channel features such as steps or riffles, and channel width expansions that promote natural deposition and riffle formation. Such actions, if implemented across the entire Middle Reach, have the potential to raise the water surface profile and significantly improve winter habitat conditions for rearing Coho. The key would be to implement actions that help the channel bed to aggrade at a faster rate than the floodplain. ESA has found that channel width expansions, which engage bed load, have the potential to cause several feet of bed aggradation that typically outpaces overbank deposition from suspended load.

Though the Upper and Lower Reaches are both confined and provide little opportunity in terms of activating existing floodplain habitat, the cause of the confinement presents different opportunities to improve habitat between the two reaches. The valley hillslope confinement of the Upper Reach likely offers relatively limited opportunities for rearing habitat improvements in contrast to the incised Lower Reach. Simple actions that create velocity breaks in confined channels such as large boulders or large wood are likely the only actions that would improve conditions in the Upper Reach. These actions affect velocities on a relatively small spatial scale and are therefore likely to only result in modest increases in habitat area during low-mid base flows. Such actions also have the potential to increase velocities and turbulence in other portions of the channel to create a diversity in habitat conditions.

The Lower Reach is mostly confined by incision into the adjacent terraces and does provide opportunity for increasing winter habitat conditions given the relatively low valley confinement. Grading in large floodplain bench nodes or expansions within the terraces not only immediately increases the amount of winter rearing habitat, but also has the potential to promote deposition that could raise the channel bed and downstream base level. If implemented across the entire Lower Reach, this has the added potential to promote aggradation and increase water surface elevations that propagate upstream, improving activation of habitat in the Middle Reach. Combining the potential actions for the Middle Reach with the potential actions for the Lower Reach could produce systematic changes to the channel bed profile and improvements in winter habitat conditions for rearing Coho.

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